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New Initiatives in High-Altitude Aircraft

In 1953, military aviation was in transition from subsonic to supersonic flight. Chance-Vought delivered the last propeller-driven fighter, an F4U Corsair, to the Navy in February. Three months later, the YF-100A, produced by North American Aviation for the Air Force, became the first service supersonic fighter—the start of the Century series. These were made possible by more powerful turbojet engines such as the Pratt & Whitney J-57, which went into production in 1953. Speed, however, is but one of the familiar trinity of major military aviation goals—higher, faster, farther. Higher altitudes meant less vulnerability for bombers and reconnaissance aircraft. The altitude goal frequently mentioned during the period was 30 500 meters. Greater range was not neglected as a goal, but global bases and in-flight refueling sometimes made it possible to compromise range in favor of other goals. In addition, military aviation planners during the 1950s felt the keen competition of guided missiles, which were in rapid ascendancy. The rivalry between aviation and missile men was strong.

From late 1952 to early 1954, three men of diverse backgrounds initiated proposals for achieving flight at very high altitudes. One was an Air Force major stationed at Wright Field, John D. Seaberg; another was a famous airplane designer, Clarence L. (Kelly) Johnson of Lockheed Aircraft; and the third was a lone British inventor with a novel idea, Randolph Rae. These initiatives and the activities they generated proceeded concurrently with, but largely independent of, the NACA research described in the previous chapter. The initiative of Seaberg led to the new altitude capability of the B-57; Johnson's led to the extraordinary U-2 high-altitude reconnaissance airplane; and Rae's led to his personal disillusionment, but new interest within the Air Force for using liquid hydrogen in aircraft.

Origins of Very-High-Altitude Aircraft at Wright Field

At the outbreak of the Korean war, John D. Seaberg, an aeronautical engineer at Chance-Vought, was called back to active duty as an Air Force major. Seaberg, who had served as an engineering and base executive during World War II, was assigned to the new development office for bombardment aircraft at Wright Field. Late in 1952, he went to his boss, William E. Lamar, with some new ideas about achieving flight at very

high altitudes. Seaberg saw in the new generation of turbojet engines, with their inherent high altitude potential, the opportunity of matching engine and airfoil to achieve an airplane of low wing-loading capable of higher altitude operation than anything yet conceived. The ideal application for such an airplane was reconnaissance; the high altitude would make detection very difficult and provide protection until effective countermeasures were developed.[1]

By March 1953, Seaberg's idea had jelled into a set of specifications for preliminary design studies by aircraft manufacturers. Operating conditions selected were an altitude of 21 340 meters or higher, a range of 2800 kilometers, and subsonic speeds. Propulsion was to be by turbojet or turboprop suitably modified for the high altitude operation. The airplane would carry a crew of one and photographic equipment weighing between 45 and 318 kilograms. No armament or ejection equipment was provided, in keeping with the objective of minimum gross weight and high altitude for protection. The contractors were to supply design specifications suitable for a development contract, a recommended engine, and a list of major development problems anticipated.[2]

Seaberg and Lamar decided to bypass the big aircraft manufacturers in favor of smaller companies because, believing that production would be small, they thought the smaller firms would give the studies a higher priority. There was no bidding; Bell Aircraft, Fairchild Aircraft, and Glenn L. Martin were called in to discuss the studies, and all three were very interested. The Air Force talked to no one else. Contracts to the three were let beginning 1 July 1953 and ran to the end of the year. Bell and Fairchild were asked to design a new airplane; Martin, builder of the B-57 bomber and RB-57 reconnaissance airplane, was asked to study modifications to the RB-57 to meet the more stringent altitude requirements.[3]

Wright Field evaluated the three studies in early 1954 and had the contractors present the study results during the first part of March. Bell proposed a twin-engine airplane; Fairchild submitted a single-engine design; and Martin discussed modifications to the RB-57, including a larger wing (fig. 25). All used Pratt & Whitney J-57 engines, modified for high altitude operation and initially designated J-57-P19 (later J-57-P37).[4]

Lt. Col. Joseph J. Pelligrini, attached to a reconnaissance unit at headquarters of the Air Research and Development Command (ARDC), visited Wright Field in mid-March, saw the Martin proposal as a fast way of meeting an urgent need of the Air Force in Europe, and requested Wright Field to send ARDC headquarters a list of necessary RB-57 modifications within a week.[5] The following month, Seaberg went to ARDC headquarters in Baltimore and gave a briefing on the three studies. Attending was Lt. Gen. Thomas S. Power, who succeeded Lt. Gen. Donald Putt that month as commander of ARDC. Power was so impressed that he had Seaberg repeat the briefing at Strategic Air Command headquarters the following day. Seaberg gave a third briefing at Air Force headquarters early in May 1954.[6] Interest in high-altitude reconnaissance aircraft increased and Seaberg had every reason to believe his idea would soon become a reality. Two weeks after his third briefing, however, a new proposal for a high-altitude airplane, from Kelly Johnson of Lockheed Aircraft Company, reached Seaberg's desk with a request for an evaluation. This proposal would lead to a series of significant events in aeronautics, politics, and diplomacy.

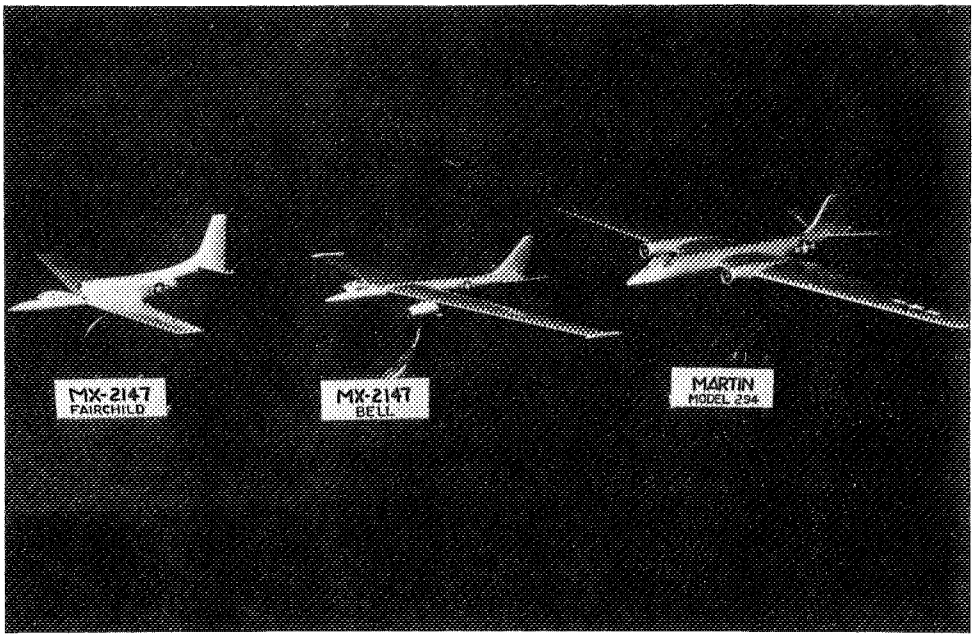

Fig. 25. Models of Fairchild, Bell, and Martin high-altitude reconnaissance airplanes from design studies conducted for the Air Force during the second half of 1953. All three used Pratt & Whitney J57-P19 engines. The Bell (X-16) and Martin (B57-D) designs were chosen for development, but only the latter was completed and is flying today as the RB-57F. (1954 photograph courtesy of W. E. Lamar and J. D. Seaberg.)

Clarence L. (Kelly) Johnson, chief engineer of Lockheed Aircraft at Burbank, California, since 1952, was already a legend among aircraft designers. He had designed and built the prototype of the first U.S. jet fighter, the F-80, in 143 days. He had gone on to design the F-90, the F-104, and many others. He had his own special brand of management and operations known as the "Skunk Works." He condensed his management philosophy to "be quick, be quiet, be on time."*

Johnson's unsolicited proposal to the Air Force came as no great surprise at Wright Field. Johnson had the confidence of and was accustomed to dealing with the highest levels in the Air Force and there was no reason for those officers to conceal their interest in very high-altitude flight from him.

As the designer of the Air Force's F-104 fighter, Johnson had proposed to use its fuselage, a larger wing to achieve an altitude of about 20000 meters, and the General Electric J-73 turbojet engine. In his review of the proposals at Wright Field, Seaberg was not impressed with Johnson's selection of the J-73 for extremely high altitude

*Johnson used a set of 14 operating rules for the Skunk Works including: almost complete control by project manager; a strong but small project office; an "almost vicious" restriction of the number of people connected with the project; a simple, flexible drawing system; minimum paperwork; thorough and periodic cost review; authority to subcontract; tight inspection; flight testing; prior specifications; timely funding; mutual trust; tight security; and rewards based on performance. Interview with C. L. Johnson and Ben Rich, Burbank, 2 May 1974.

flight. He felt that the more powerful Pratt & Whitney J-57, modified for high altitude operation, was required. However, it was too large to fit into the F-104 fuselage, so a modified fuselage would also be required. Since the proposals for the Martin RB-57 modification and the Bell X-16 had been approved, Seaberg saw no need to develop a third airplane and recommended against Johnson's proposal.[7] Seaberg's view was supported by the Air Force. The high-altitude B-57D was subsequently built; the Bell X-16 was initiated but cancelled in mid-1956.

When the Air Force turned Johnson down, he did not give up and a fortunate turn of events gave him a big break. In 1954, the role of the guided missile was rising rapidly, and the Department of Defense formed a number of advisory groups in mid-1954 to examine the various aspects of military planning and weapons. James R. Killian became chairman of a committee on surprise attack and was aided by several panels. One of these was on intelligence. During the course of its work, the panel learned about Johnson's proposal for a very high-altitude reconnaissance airplane and liked it. Killian was convinced of its merits and soon others, including Charles Wilson, Secretary of Defense, and Allen Dulles, director of the Central Intelligence Agency, also became convinced. It was known that the airplane had been proposed to the Air Force but that the Air Force had decided not to develop it.*

Johnson's proposal was taken to President Eisenhower during the latter part of November. As described by Eisenhower:

> Back in November 1954, Foster Dulles, Charlie Wilson, Allen Dulles, and other advisors had come to see me to get authorization to go ahead on a program to produce thirty special high-performance aircraft at a total cost of about $35 million. A good deal of design and development work had already been done. I approved this action.[8]

Eisenhower decided that the funding and direction of the project would be under the CIA and Richard M. Bissell, Jr., was selected to head it. The Air Force was to contract with Lockheed for development of the airplane, designated the U-2. Because of the sensitivity of the project, the Air Force handled its part directly from headquarters.[9] On 9 December 1954, Trevor Gardner, assistant secretary of the Air Force for research and development, visited Robert Gross and Kelly Johnson at Lockheed and told them to go ahead.[10] The Skunk Works swung into action and the first U-2 flew eight months later. It was powered by a Pratt & Whitney J-57-P37 turbojet engine, the engine Seaberg had argued was necessary.†

The U-2 (fig. 26) was capable of flying at altitudes above 21 300 meters at a speed of about Mach 0.75 (about 800 kilometers per hour at its altitude). The first operational

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*Members of the Killian committee were briefed on Air Force plans for the B-57D and the X-16 by John D. Seaberg in the office of Lt. Gen. Donald Putt, deputy chief of staff for development, USAF, on 18 Nov. 1954. Seaberg also discussed the Fairchild and Johnson proposals and indicated that Johnson's airplane performance could be improved if the J-57-P37 engine replaced the J-73 proposed by Johnson. Letter from Seaberg to author 28 June 1976, with enclosures.

†Seaberg says that, to this day, Johnson tells him, "You had a chance to buy the U-2 and didn't do it"; and he counters with, "Kelly, you picked the wrong engine." Interview with Seaberg, 23 Nov. 1973; letter from Seaberg to author, 28 June 1976.

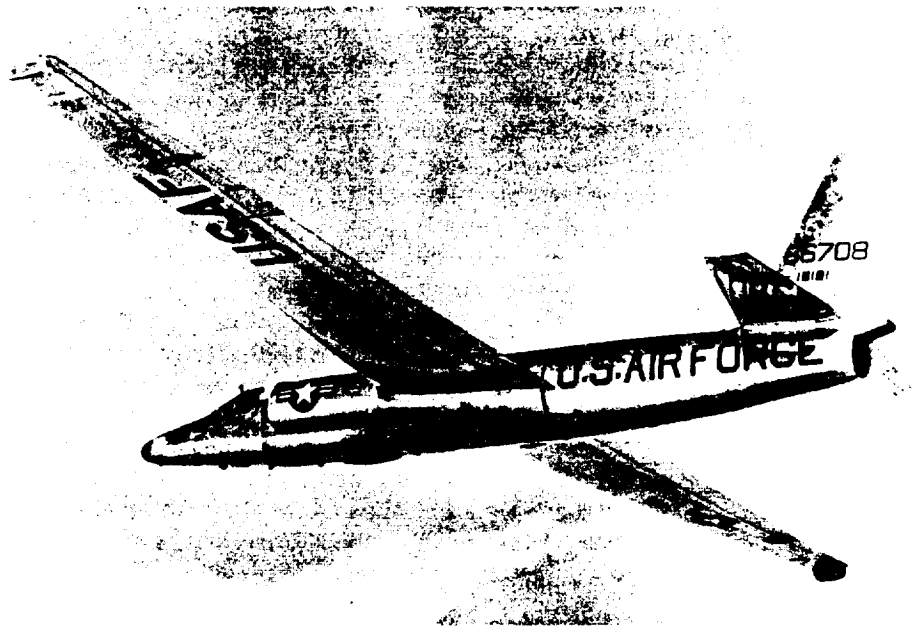


Fig. 26. Lockheed U-2 airplane, proposed in 1954 and in active government service continuously since 1956. Its capability for sustained flight at very high altitudes is still unmatched by any other airplane. (1963 photograph courtesy of Lockheed Aircraft Corp.)

flight occurred in the spring of 1956. The government chose research by the National Advisory Committee for Aeronautics as the cover for the covert reconnaissance operations of the airplane, but kept the NACA in the dark about its real purpose. Early U-2s carried NACA markings (and, later, NASA markings) and obtained data on high-altitude meteorological phenomena.[11] These data made significant contributions to a better understanding of turbulence, wind shears, and jet streams. In 1973, the NASA began using the versatile U-2 in its earth resources program.

In the early spring of 1954, in the midst of Seaberg's plans and before Johnson's proposal reached his desk, a British inventor brought a new and novel concept for an airplane and engine, called Rex I, to Wright Field. Unlike other airplanes, Rex I used liquid hydrogen as fuel.

Rae's Rex I Proposal

There was nothing unusual about the visitor who came to Wright Field on the chilly, overcast day of 24 March 1954. He was one of dozens who were processed through the large visitor's center adjoining the security fence to go to one of the many buildings of the huge Wright Air Development Center. Typical also was the reason for his visit. He was bringing an idea, neatly packaged in a brochure, and seeking a contract. The Center receives hundreds of unsolicited proposals annually and is geared to evaluate them. As with most such proposals, this one was destined to be rejected. What was

unusual, however, was the novel solution proposed for a difficult problem, the sensitive nature of the subject, and the timing. The proposal triggered waves of interest within the government, and there followed a series of events involving hydrogen that extend to this day—events that shuttled the proposer to the sidelines and left him bewildered and embittered. His name is Randolph Samuel Rae (1914–).

Randy Rae is a quiet, soft-spoken man with the imagination and creativeness that mark the practical innovator and inventor. He received his engineering education at a Swiss technical school and began his career in electronics and underwater detection systems for locating submarines. He worked for the British Admiralty from 1939 to 1948, serving in four research and development groups in underwater acoustics, aerodynamics, thermodynamics, and propulsion, rising to the position of a principal scientific officer. He came to the United States in 1948 and worked in the Applied Physics Laboratory of Johns Hopkins University for four years. He started in aerodynamics and developed a supersonic diffuser for ramjet engines and later was placed in charge of the development of a complete guided missile system. More at home with technical details than overall project management, Rae soon was immersed in a difficult missile stability and control problem and devised a solution involving a gyro with a mechanical feedback. The system was put out for bid and a small company, Summers Gyroscope, won the contract. Rae met a kindred soul in dynamic, innovative Thomas Summers.[12]

The missile development that Rae was managing used a ramjet engine for propulsion. A ramjet operates at high altitudes and speeds, but as with all air-breathing engines, it is altitude-limited. The ramjet's altitude-speed limitations set Rae to thinking about other solutions to the problem in April 1953. Was there a way to operate at very high altitudes but at lower speeds, specifically in the subsonic speed range? The rocket was not the answer, for although it operates independent of the atmosphere, it is very inefficient at low speeds. Could he combine the altitude-independent feature of the rocket engine with a propulsion system efficient at low speeds? The most efficient means for aircraft propulsion at low speeds is the propeller, but it is, of course, altitude-limited. Rae conceived of using a rocket as a gas generator to drive a turbine which, through suitable gearing, would drive a large propeller. Such a propulsion system had no place in the high-speed, high-altitude operating regime of the Navy's work at the Applied Physics Laboratory. Rae became so intrigued with his concept that he left APL/JHU to work full-time on the new propulsion system. He soon learned the handicaps a lone inventor faces. He needed not only monetary support but a corporate identity as well. He turned to his friend, Thomas Summers, who very generously offered both, although propulsion was a far cry from gyroscopes and instruments.

Rae joined Summers in September 1953 and began analysis of what he called the Rex engine. The week before Christmas, Summers engaged Homer J. Wood, a mechanical engineering consultant. Wood had left the Garrett Corporation, makers of small gas turbine engines and other aircraft components, in October after ten years service during which he became assistant chief engineer in charge of turbomachinery. Wood assisted in the analysis and design of Rae's new engine.[13]

By March 1954, Rae was ready to present his idea to the government. He visited the headquarters of the Air Force Air Research and Development Command (ARDC),

then located in Baltimore, and discussed his idea with Col. Donald Heaton, chief of the aeronautics and propulsion division, and Lt. Col. Langdon F. Ayers, who headed the propulsion branch. The two were engaged in planning research and development to increase the altitude capability of aircraft, and Rae's idea caught their interest. They suggested that he visit Wright Field and discuss the proposal with the specialists there.[14] This was what brought Rae to Wright Field on 24 March 1954, with brochures describing the proposal.

Rae presented his proposal to a group in the new developments office of WADC and passed out copies of his brochure. It bore the date of February 1954 and the title, "REX-1, A New Aircraft System" (fig. 27). Rae described it as "a lightly loaded low speed plane having an exceptional L/D (lift/drag) characteristic." By lightly loaded, he meant a low weight per unit area of wing; the aircraft resembled a low-powered glider. The speed of about 800 kilometers per hour would make a military airplane quite vulnerable were it not for the very high operational altitude that Rae proposed—over 24000 meters, which was well above the capability of other aircraft and hopefully beyond the range of antiaircraft weapons. What stirred the interest of the Wright Field audience was the novel engine that Rae proposed: a three-stage turbine engine using liquid hydrogen and liquid oxygen (fig. 28). Ahead of each turbine was a small combustion chamber. All of the hydrogen and part of the oxygen were fed to the first combustion chamber. This partial combustion of the hydrogen produced a gas temperature of about 1100 K, the then practical limit for turbine materials. After

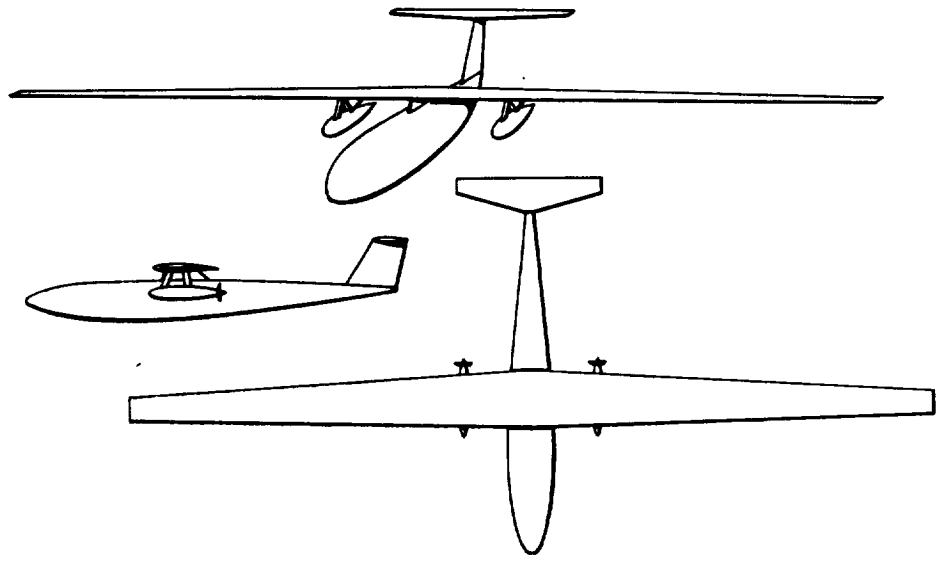


Fig. 27. Sketches of REX-1, a low-speed, high-altitude airplane using liquid hydrogen, proposed to the Air Force by R. S. Rae in Mar. 1954. Gross mass, 32660 kg; empty mass, 16330 kg; wing area, 434 m^2; power, 1790 kW (2400 hp); take-off speed, 113 km/hr; cruising speed, 640–800 km/hr at 26000 m altitude; range, 10000 km. When empty, it could glide an additional 1000 km. From brochure "REX-1, A New Aircraft System," by R. S. Rae, Summers Gyroscope Co., Feb. 1954.

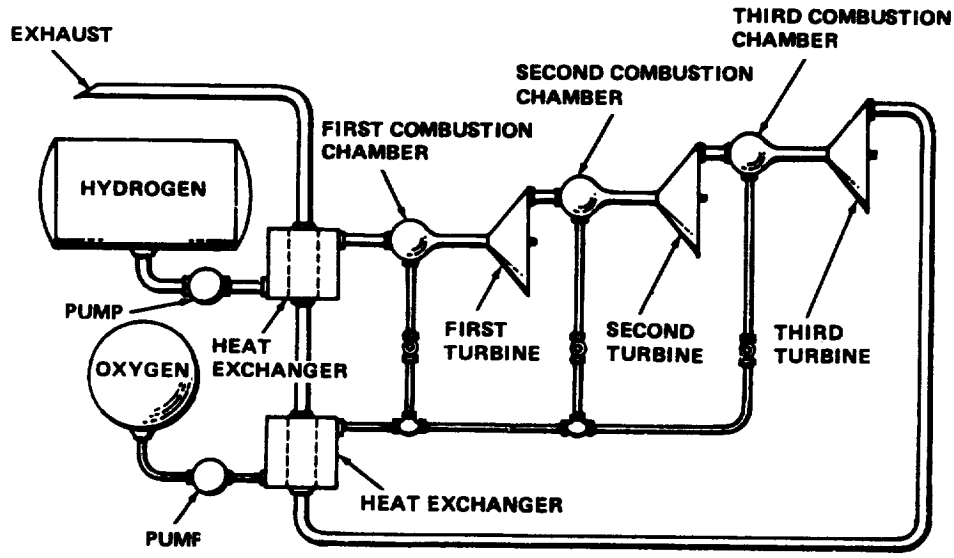


Fig. 28. Schematic of Rex 1 engine. Liquid hydrogen and oxygen, gasified by passing through heat exchangers, flow to three small combustion chambers. The hot gases drive three turbines connected to a common shaft. The gases for the second and third turbines are a mixture of the exhaust from the previous turbine and combustion gases. After the third turbine, the exhaust gases supply heat for the heat exchangers and then discharge. From the brochure "REX-!, A New Aircraft System," by R. S. Rae, Summers Gyroscope Co., Feb. 1954.

leaving the first turbine, the gases were reheated by adding additional oxygen and burning. The process was repeated for the third turbine. After leaving the third turbine, the gases passed through heat exchangers to heat the incoming liquid hydrogen and liquid oxygen.* Rae was attracted to hydrogen by its high specific heat, relatively low combustion temperature, and high energy content.[15]

The three high-speed turbines, on a single shaft, were geared down to drive a propeller. The conceptual engine was very compact (fig. 29). With both liquid hydrogen and liquid oxygen on board the aircraft, the turbine engine was independent of altitude. Rae proposed to use the turbine engine to drive a large propeller which provided the propulsive thrust by accelerating atmospheric air. The propeller, obviously, depended very much on altitude; the size of the propeller needed for thrust at high altitude later became an issue in evaluating the proposal. After pointing out the military advantages of a high-altitude aircraft, the brochure ended with a low-keyed request: "The Summers Gryoscope Company is desirous of obtaining a Government contract to develop the revolutionary REX-I aircraft system."

As is usual in such cases, Rae left that day wondering how his proposal would be received, after the noncommittal attitude of the Wright Field listeners. In fact, his proposal caught the attention and interest of many in the Air Force and several

*Rae used an initial pressure of 69.7 atm, a final pressure of 0.67 atm, and a heat exchanger efficiency of 90%. He quoted an achievable specific fuel consumption of 1 lb/hp · hr (0.61 kg/kW · hr) and gave data indicating this could be attained with a four-stage turbine system with a turbine efficiency of 50%. He had analyzed both three- and four-stage turbines; by specific fuel consumption, he apparently meant both hydrogen and oxygen.

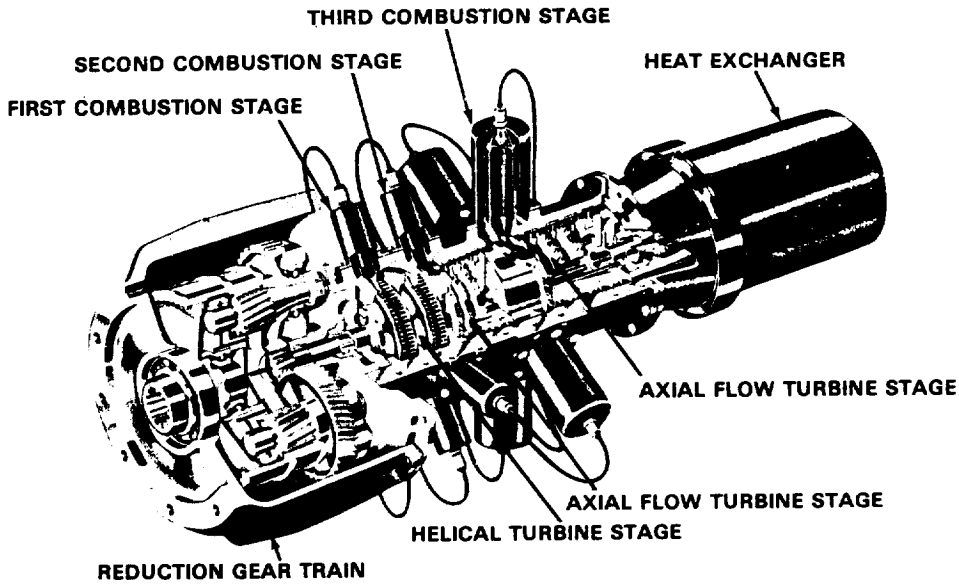


Fig. 29. Drawing of Rex I engine showing the heat exchanger, hydrogen-oxygen combustors, and three turbines. In the foreground is a reduction gear train transmitting power from the high-speed turbines to the engine application which, in the first proposal, was a propeller. From the brochure "REX-1, A New Aircraft System," by R. S. Rae, Summers Gyroscope Co., Feb. 1954.

analyses were started immediately. In response to a request for more information, Rae sent considerable detail about the proposed engine with a cost analysis. The cost was estimated to be on the order of $3 million a year for three years.[16]

In an analysis completed in May, Weldon Worth, R. E. Roy, and R. P. Carmichael examined propulsion aspects of the proposal and concluded: "There are numerous examples of optimism in the proposal but nevertheless, if the development does not bog down under adverse problems that result from impractical features, the small engine size and weight, the reasonably low fuel consumption, the high altitude combustion capability of hydrogen, and the surprising aircraft performance present a stimulating approach to a high altitude performance regime well beyond present aircraft capabilities." They added that there were other possible ways of achieving the same flight regime and discussed adverse technical factors that were based on hydrogen's characteristics and the possibility, from preliminary estimates of the propeller laboratory, that a much larger propeller than proposed might be necessary. Large, insulated lightweight tanks and a circulating gas–heat exchanger system were considered major development problems; these and a larger propeller or fan could substantially increase rize and mass of tankage, engine, and gearing between engine and propeller.[17]

In Rae's opinion, Wright Field's principal objections to his proposal centered on mass estimates and propeller size. He was kidded that his airplane would need a runway with trenches on each side of the wheels to accommodate propellers 12 meters in diameter. Rae believes he was vindicated later on both these points, but at the time he felt that the brickbats were coming at him thick and fast.[18]

Other Engines and Hydrogen Proposals

Rae's proposal to use liquid hydrogen as an aircraft fuel was, of course, not new nor was his engine the only possibility for using it. In 1937, von Ohain found that his experimental turbojet engine worked well on gaseous hydrogen (p. 73). In 1954, J. M. Wickham of Boeing studied the use of hydrogen for a strategic bomber powered by turbojets. For a subsonic cruise–supersonic dash flight, Wickham concluded that hydrogen gave a theoretical 30 percent increase in range over the use of a hydrocarbon fuel.[19]

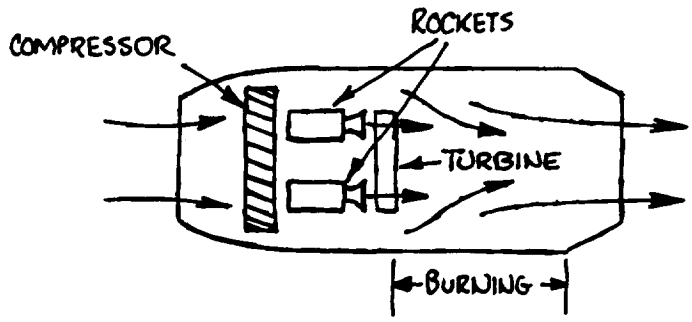
Wright Field was also well aware of another type of engine capable of using liquid hydrogen which—like Rae's Rex I—used liquid oxygen for combustion independent of altitude. This was the turborocket, a combination of rocket and air-breathing engine, which went back as far as a suggestion by Goddard (p. 74). During World War II, the Germans developed such an engine using a turbine, driven by decomposed hydrogen peroxide (steam and oxygen) to power an axial-flow compressor. The fuel was injected into the air stream and burned. The British had also investigated the turborocket by 1945, and Wright Field became interested after the war. Alfred M. Nelson, an analyst at Wright Field, reported his study of rocket-driven, turbine-compressor engines in December 1946 (fig. 30, top). Nelson described an engine where the rocket provides fuel-rich hot gases to power a turbine which drives a compressor. After leaving the turbine the fuel-rich gases burn in the air in the aft section of the engine. The hot gases expand through the exhaust nozzle to produce thrust. One of the best known champions of the turborocket was William C. House, who proposed a cycle in 1949 while an employee of the Aerojet Engineering Corporation.* House examined a number of bipropellants including liquid hydrogen and liquid oxygen. He apparently proposed this combination to the Air Force in September 1953 and later, but nothing came of it (fig. 30, bottom).[20]

With all this previous experience both in hydrogen as a fuel and in hybrid engines, why did the Air Force become so interested in Rae's proposal? The reasons came less from the technical interest of experts at Wright Field than from Air Force managers of research and development at Headquarters. They were under increasing pressure from other Air Force elements to develop means for increasing the operational altitude of aircraft. Rae's idea stirred interest because it was timely.

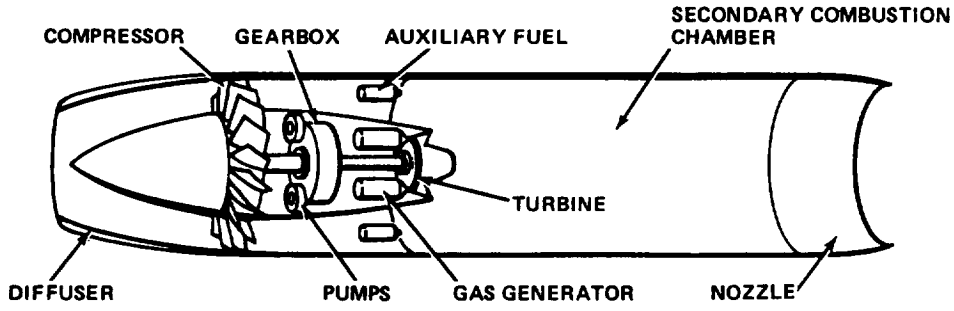
Air Force Evaluation of Rex I

In June 1954, Col. Omar E. Knox sent the WADC evaluation of Rae's proposal to ARDC Headquarters. Three laboratories, including the power plant laboratory, contributed to the evaluation. The basic engine was considered technically feasible, but considerable doubt existed regarding the technical feasibility of the propeller, hydrogen system, and airframe. If the airplane could be built as predicted, it would be

*Aerojet applied for and was granted a patent in Sept. 1950, but it was issued under a secrecy order because of potential military application. That order was removed and House received Patent 31 110 153 in Nov. 1963.



NELSON SKETCH OF TURBOROCKET, (1946). (COURTESY OF R.P. CARMICHAEL.)



AEROJET SCHEMATIC OF AIR TURBOROCKET CIRCA 1964. (COURTESY OF W.C. HOUSE.)

Fig. 30. Schematic of air turborocket engines, also called simply turborockets, by Alfred Nelson in an Air Force memorandum in 1946 and from an Aerojet brochure ca. 1964. (William House of Aerojet championed this type of engine from 1949 into the early 1960s.) Rocket combustion gases drive a turbine which drives an air compressor. The fuel-rich turbine exhaust gases burn in the air stream and additional fuel is injected. These concepts, mentioned by Robert Goddard in 1937, were developed in Germany and England during World War II.

extraordinary in performance. Rae was praised as an imaginative and competent engineer, as evidenced by his contributions while working for the Applied Physics Laboratory and by the analysis he submitted. At the same time, however, the evaluators questioned the wisdom of placing development of an airplane with a company with so little systems capability. The cost estimate was considered unrealistic. Knox recommended against accepting the proposal, but suggested that ARDC look into overall propulsion and airframe problems of aerodynamically supported aircraft at extreme altitudes. That was exactly what Heaton and Ayers had been doing and why they were interested in Rae's proposal. They were not satisfied with WADC's negative response.[21]

In July 1954, Col. Paul Nay replaced Heaton as chief of the ARDC division of aeronautics and propulsion and was soon involved in concepts for achieving high altitude flight, including Rae's. On 9 August, Rae and Wood visited Nay and Ayers at ARDC headquarters in Baltimore and the following day Rae sent his proposal to Nay.

It contained details on program phasing and cost. Rae estimated first year costs at $1.9 million and annual costs for the next three years at $3.1 million. Included was a $50000 sum to contract with Lockheed Aircraft Company for an airframe analysis. Rae stressed that hydrogen was more a working fluid than a fuel and that its complete oxidation was not desirable. He had done additional analysis, and the application for the long-range, high-altitude airplane included a reconnaissance radar picket as well as a bomber. Rae did not attempt to downgrade the potential problems and indeed mentioned several. He also pointed out that hydrogen could be used as a fuel in regular turbojet engines and that engine cycles using hydrogen had common elements that justified immediate component development. He requested the Air Force to provide a supply of liquid hydrogen in the Los Angeles area for component testing. To emphasize his point on the versatility of hydrogen, he sent the Air Force a report describing an engine cycle which later became known as Rex III.[22] It used air as the oxidizer and will be described later.

Rae's visit to ARDC and the revised proposal strengthened the belief of Nay and Ayers that Rae's concept should be further investigated. Three weeks after the visit, on 31 August 1954, Nay directed WADC to prepare a development plan for high-altitude engines, including the Rex I engine. He emphasized the need for long-range, high-altitude aircraft and argued that the optimum speed had not been established. This was a crucial point, for most of the emphasis was on aircraft capable of supersonic speeds, whereas the propeller-equipped Rex I was subsonic. Nay pointed out that WADC emphasis was on fans and compressors for jet engines rather than propellers, and the latter needed attention along with the hydrogen-oxygen reheat turbine cycles conceived by Rae. WADC should—as appropriate—conduct studies, experiments, and preliminary development of promising high-altitude propulsion systems, including Rex I. Summers Gyroscope was regarded as capable of analytical and experimental work with their existing facilities. WADC was encouraged to develop a working arrangement with an engine manufacturer and take maximum advantage of existing hydrogen technology, including rocket experiments. The directive was accompanied by a transfer of funds to accomplish it.[23]

The directive was clearly much broader in scope than merely contracting with Summers for the use of Rae's idea. The directive addressed the general problem of high-altitude propulsion, of which Rae's engine was one possible solution. While Summers was endorsed as capable of analytical and experimental work with their existing facilities, ARDC also suggested a working arrangement with an engine manufacturer. This constituted a limited endorsement and was not an arbitrary decision. Procurement experts had investigated Summers Gyroscope as a contractor, and the top procurement official of ARDC visited the company to satisfy himself about its capabilities for limited work on the concept.[24]

Other Reactions to Rae's Proposal

Wright Air Development Center took no action on the directive during the remainder of 1954, but there were other developments. The Fuels and Propulsion Panel of the Air Force Scientific Advisory Board considered the Rex I engine at its 29

September 1954 meeting.* The panel saw Rex I as an interesting cycle of potential importance and recommended that the development of non-air-breathing chemical engines should be actively pursued. Rex I was viewed as only one of several possibilities. The panel also recommended that a broad general study be made before development of the Rex I engine.[25]

According to Rae, the staff of the scientific Advisory Board asked him to go to the NACA Lewis Flight Propulsion Laboratory in Cleveland and give a briefing on Rex I.[26] He did so in November 1954, presenting the Rex concepts and various cycles to Abe Silverstein.†

The situation in late 1954 was tense for Rae. He had distributed fifteen copies of his brochure and backup technical data, given several briefings, and was aware that the Air Force was very interested. He had to defend his idea against a number of criticisms. He had conducted enough analysis to believe in the soundness of his approach and wanted support to develop it, but this appeared slow in coming. On the Air Force side, there was great interest in Rae's concepts—probably more than he suspected—for it touched on a critical need. The power plant laboratory, however, had reservations about the practicality of Rae's engine and how far to go with Summers Gyroscope as a contractor, and these points were clearly made in the WADC evaluation. The new development office of the weapon systems directorate, where Seaberg was pushing other high-altitude concepts, was negative about the Rex concept. Storm signals were flying for those perceptive enough to observe them.

Late in 1954, when Kelly Johnson was developing the U-2, Randy Rae was still seeking a way to get the Air Force to move on his proposal. It became clear to him that he needed to associate with a company having experience with turbines, the major component of his propulsion system. He knew Bertram N. Snow (1901–1966), dynamic vice president of the Garrett Corporation, makers of small turbines and many other components for the aviation industry. He approached Snow and later J. C. (Cliff) Garrett, founder and president of the company.[27] Garrett and Snow were very interested in Rae's ideas, but being shrewd and perceptive businessmen, they wanted to sound out Air Force interest in Rae's ideas and Garrett as a suitable contractor before they committed themselves. After assuring themselves on these questions, they began negotiations to acquire the Rex engine from Rae and Summers.[28]

WADC Response to ARDC Directive

Meanwhile, the power plant laboratory at Wright Field started actions responsive to the ARDC directive of August 1954. Four procurement requests were initiated during the first quarter of 1955. On 6 January, PR 303 was initiated with $750000 for a

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*Present were Prof. C. P. Soderberg (chairman), William M. Holladay, Allen F. Donovan, William D. Rannie, Addison M. Rothrock, Gale Young, and Mark Mills.

†An interesting speculation is whether Rothrock, who heard the Rex-I presentation at the 29 Sept. 1954 SAB meeting, transmitted information about it to Lewis earlier than November 1954, or asked the laboratory to investigate hydrogen, or asked the SAB staff to send Rae to Lewis. The last appears to be the most probable (p. 97). Rae's presentation intensified Silverstein's interest in hydrogen for aircraft, but was not the origin of his interest.

contract with Summers Gyroscope Company to explore the Rae concepts, including the study of an aircraft design. For unknown reasons, this procurement request was recalled and reinitiated with a new date, 10 March 1955. It became the subject of much controversy and negotiation.

On 14 January 1955, a second procurement request, PR 305, was initiated to investigate hydrogen as a fuel in conventional turbojet engines. Four engine manufacturers were listed as sources, but when the form reached Philip J. Richie, a procurement official of the power plant laboratory, he added five more to be solicited. The requests, sent out on 2 February, had a due date of 15 March. On 20 February, Richie received a puzzling directive from ARDC Headquarters: give the Garrett Corporation an opportunity to submit a proposal on PR 305. He reluctantly complied, but did not extend the due date. Garrett bid on this and later attempted to include the same kind of work in other proposals but was unsuccessful. On 15 June, PR 305 resulted in a contract with United Aircraft for $543000.

In recognition of the unique properties of liquid hydrogen, the power plant laboratory initiated two procurement requests for studies of liquid hydrogen tanks and insulation on 25 March 1955. PR 338 resulted in a contract with Beech Aircraft in June for $172000. PR 339 became a contract with the Garrett Corporation in October, but until then it was caught in the same web of controversy and negotiations with Garrett as PR 303.[29]

When PR 303, with Summers Gyroscope as the sole source, reached Richie in March, he decided that a talk with Thomas Summers was necessary. When Summers came to Wright Field, Richie was puzzled to find him in no hurry to submit the necessary proposal. He soon learned the reason. On 22 March, Richie was summoned to ARDC headquarters and learned that the headquarters procurement officer objected to PR 303; Garrett had acquired Summer's interest in Rex and was the company to deal with.* Richie also learned during his visit that Gen. Marvin Demler, Gen. J. W. Sessums, Col. Paul Nay, and other top officials at ARDC were very familiar with the Rex program and wanted a contract executed fast.[30]

High-Level Air Force Interest in Rex

The familiarity of top Air Force R&D officials with the Rex proposal and their desire for rapid contracting did not result solely from interest in a novel idea. The same month that Philip Richie learned of Air Force interest at ARDC Headquarters, the Fuels and Propulsion Panel of the USAF Scientific Advisory Board met at the RAND Corporation and considered superfuels.† The panel was impressed by the performance

*The date of Garrett's acquisition of Rex interests from Rae and Summers is not clear. An indenture and transfer agreement on the patents dated 18 March 1955 appears to be the earliest date. However, another indenture agreement was signed on 22 June 1955 from Rae to Garrett and Summers to Garrett. On 29 July 1955, an announcement was made at a meeting of Air Force and Garrett officials that Garrett had acquired the Summers interest in the Rex engine. Garrett File, AFSC, Andrews AFB.

†The attendees at the March 1955 meeting were Mark M. Mills (chairman), W. Duncan Rannie, Addison M. Rothrock (NACA), Edward S. Taylor, and Gale Young. Records of USAF Scientific Advisory Board, Pentagon.

potentials of two promising fuels—liquid hydrogen and boron hydrides. NACA experiments with hydrogen (pp. 97–98) were discussed and the panel recommended active development of hydrogen fuel systems and engine combinations, as well as preliminary design studies of aircraft to use these fuels. The panel also met with the SAB panel on intelligence to consider vehicle requirements. The fuels and propulsion panel concluded that the Rex engine might contribute to this application and recommended further study.[31]

The Air Force motivation for rapid action on high altitude aircraft stemmed from the U-2. Many in that service were unhappy having the CIA manage that aircraft. Even before it flew, there were discussions within the Air Force about a follow-on airplane. The possibility that the U-2 might get shot down was recognized early, so attention was focused on airplanes capable of higher speeds and altitudes. One of the problems foreseen for the U-2 was its vulnerability from engine flameout at high altitude.[32] If flameout occurred, the airplane had to descend to a much lower altitude—about 9000 meters—to restart the engine; at that time it was a sitting duck for antiaircraft fire.*

In addition to the flameout problem of the U-2, Kelly Johnson was faced with a problem of fuel loss from boil-off at very high altitudes. He had help on both problems from the Air Force and Pratt & Whitney, makers of the J-57-P37 engine. At the time, Col. Norman C. Appold, a combat pilot during World War II and holder of master's degrees in chemical and aeronautical engineering, was chief of the power plant laboratory at Wright Field. Earlier he had managed the Air Force contract with Pratt & Whitney for the J-57 and was very familiar with it. For this reason, and because he could draw on other propulsion and fuel experts in his laboratory, Appold was designated a "consultant" to Kelly Johnson. The father of the J-57 engine and chief engineer of Pratt & Whitney was Perry W. Pratt (no relation to the Pratt of P&W), and he too became closely involved with helping Johnson.

The J-57 turbojet engine normally operated on JP-4, a kerosene-like fuel. Johnson needed a fuel of lower volatility than JP-4 to minimize fuel loss during climb to the cruising altitude and during cruise. When the airplane took off, its fuel was at ground temperature. At high altitude, the combination of still-warm fuel and reduced pressure caused the more volatile portions of the fuel to boil away through the tank vents. Second, he needed a fuel with as high a combustion efficiency and flameout limit as he could get. Research showed that low volatility fuels had lower combustion efficiency than those of higher volatility, but this could be offset somewhat by improvements in the fuel injection system. Other research showed that fuels of low volatility had high flameout limits. In the end, Johnson, Appold, and Pratt selected a lower volatility fuel developed with the assistance of the Shell Oil Company research laboratories.[33]

During the course of studying the fuel-engine relationships for the U-2 and J-57, Appold and the fuel experts at the power plant laboratory considered a variety of fuels,

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*On 3 May 1960, two days after Francis Gary Powers was shot down over Russia, NASA put out a press release stating in part that "the pilot reported over the emergency frequency that he was experiencing oxygen difficulties." Propulsion engineers familiar with the altitude performance of jet engines assumed Powers had a flameout and descended to a lower altitude to relight. Powers, however, insists that he was shot down at operational altitude. Gary Powers with Curt Gentry, *Operation Over-Flight: The U-2 Spy Pilot Tells His Story for the First Time* (New York: Holt, Rinehart and Winston), pp. 144, 201-202, 302, 323, 351-352.

including some of high volatility such as methane and liquid hydrogen. Methane was available in quantity, but liquid hydrogen was quickly dismissed because it was not.[34] This was the same period in which Rae was promoting the use of hydrogen in his Rex engine. Appold was well aware of Rae's Rex proposals and was involved in the actions regarding them. Sometime during the discussions between Appold, Johnson, and Pratt, the seed of the idea to use hydrogen was planted and grew.* It matured into action in 1956 as we will see later.

Long Summer of Negotiations

Stimulated by the high-level interest in Rex from his March 1955 trip to ARDC Headquarters, Philip Richie returned to his procurement duties at Wright Field's power plant laboratory expecting to let a contract on Rex within a month.[35] This was not to be. In fact, what followed was an extraordinary series of proposals by Rae and Garrett on the one hand and revisions of statements of work by personnel of the power plant laboratory on the other, with many negotiations between the two groups. These actions reverberated up and down the line, affecting virtually every level of management in Air Force research and development as far as the Assistant Secretary. At the root of the problem was a fundamental difference in approach between Rae and Garrett on the one hand and Appold and his associates at the power plant laboratory on the other. Rae insisted on a contract for the complete airplane powered by his turbine engine. This differed from the usual Air Force practice. An airframe manufacturer usually is the prime contractor for an airplane, including its tanks and fuel system, with the engine furnished either by the government or by an engine manufacturer, as a subcontractor to the airframe manufacturer. Garrett, as a manufacturer of aircraft components and small turbine machinery, had often been a subcontractor but went along with Rae's desire to obtain the complete aircraft contract. Obviously, Garrett intended, at some point, to either license or work jointly with an airframe manufacturer.

The Air Force, on the other hand, respected Rae's position as the originator of a novel solution to a difficult problem, but never viewed either him or Garrett as potential contractors for an entire airplane. The Air Force became extremely interested in hydrogen as a fuel and the Rex engine as a means for reaching very high altitudes, but was not fully convinced that either was practical. For these reasons, the power plant laboratory, not the weapon systems directorate, took the lead in initiating the purchase requests to explore the Rex concept and in dealing with Rae and Garrett. The laboratory wanted a step-by-step approach to determine the feasibility of using hydrogen and the Rex engine before initiating a large development effort. Necessary steps included a study of engine cycles, selection of the optimum cycle, and

*Neither Appold, Johnson, nor Pratt could recall definitely when or where the idea originated (interviews with Appold 4 Jan., with Johnson 14 Feb. and 2 May, and with Pratt 14 May 1974). The origin of the idea is less important than the interactions that occurred. Less than four months after the first U-2 flight (Aug. 1954), the NACA Lewis laboratory found that gaseous hydrogen in a turbojet combustor did not flameout as easily as jet fuel and could burn at pressures equivalent to 16000 m altitude (p. 98). No connection between the U-2 problem and the Lewis experiments has been established, but the timing is interesting.

experimental work on selected components including the fuel tank. The laboratory would review the work at each step before approving the next. This logical and conservative approach was irksome to Rae and Garrett, who were convinced they had a great idea and wanted to move fast to capitalize on it. They did decide, however, to propose a series of engines using hydrogen.

The negotiations with Garrett began on 20 April 1955 when Rae and Snow presented the Garrett proposal to Wright Field and followed it up two days later with a report. Their proposal went so far beyond what the laboratory had intended that one listener commented that it covered PR 303 "like the state of Texas covers Rhode Island."[36] Included in the proposal were three types of hydrogen-fueled engines called Rex I, II, and III.[37] All were jet propulsion engines; the propeller had disappeared. Rex I used liquid hydrogen and liquid oxygen to drive multiple turbines, with the hydrogen-rich exhaust gases dumped overboard. It was the same turbine system as Rae's original Rex I (pp. 119–121). The shaft power from the turbines was used to drive a fan which compressed incoming air (fig. 31, top). Thrust was obtained by expanding and accelerating the air through the nozzle.

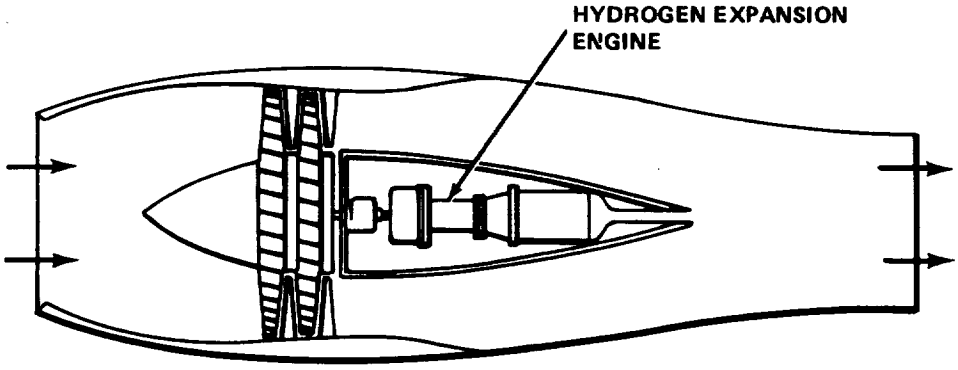
Rex II was similar to Rex I except that the hydrogen-rich exhaust gases from the turbines were burned in the air in the afterburner (fig. 31, bottom). Rex II was essentially the same concept as a turborocket (p. 122).

Rex III was quite different from the other two engines. Liquid oxygen was not used, and the hydrogen served two different functions. First, heated hydrogen alone was used to drive the turbines; and second, the hydrogen was burned with air to provide the heat for the first function. This sounds like a man lifting himself by his bootstraps, but it works (fig. 32). Hydrogen from the tank is raised to a high pressure by a pump and passes through a heat exchanger where it is heated to a sufficiently high temperature to drive the first turbine. After leaving the turbine, it is reheated in a second heat exchanger and the process repeated for the third turbine. After the third turbine, the hydrogen enters a combustion chamber where it mixes with part of the engine air and burns fuel-rich. The hot combustion gases provide the source of heat for the three exchangers that heat the incoming hydrogen. After the third heat exchanger, the hydrogen-rich gases are injected and burned in the main air stream of the engine in the afterburner. The three turbines drive the compressors for the incoming engine air and the air used to burn the hydrogen.

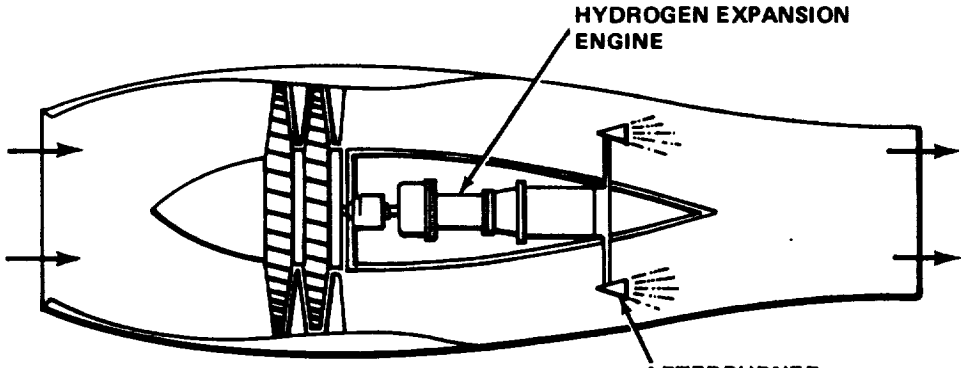
The scope of the Garrett proposal of April 1955 became an issue between the company and the power plant laboratory, as negotiations continued. In early May, Rae complained to Brig. Gen. V. R. Haugen, director of laboratories at Wright Air Development Center, that the power plant laboratory had emasculated his program. Haugen investigated and satisfied himself that the laboratory's actions were proper and invited Rae to lunch in an effort to improve relationships.[38]

On 20 May, Garrett and Air Force officials met again. Some changes in the description of work were made by mutual consent. Garrett, willing to invest capital in developing Rex engines, sought a development contract, but Appold rejected this as untimely. Both parties, however, agreed on another matter: prompt action to ensure an adequate supply of liquid hydrogen.[39]

The government owned five acres of land within Garrett's facility at Phoenix, and this was studied as a possible site for a government-owned hydrogen liquefaction plant



REX I ENGINE SYSTEM



REX II ENGINE SYSTEM

Fig. 31. Rex I and II engine systems as proposed by Rae in 1955. The Rex I engine, first proposed in 1954, drove a two-stage air compressor and the air expanded through the exhaust nozzle for propulsive thrust. In the Rex II system, fuel was added to the airstream. Rex II was a form of turborocket that had been studied in Germany, England, and the U.S. in the 1940s. From R. S. Rae, "Various Engine Cycles Using Hydrogen as a Working Fluid and as a Fuel," Twelfth Annual Flight Propulsion Meeting, Institute of Aeronautical Sciences, Cleveland, 14 Mar. 1957.

for Garrett's experimental needs. In June, William C. Meister, a government industrial specialist, reported that the site was satisfactory. He also reported that liquid hydrogen plant details could be obtained "from standard plants built in the past."[40] He was probably thinking of the Bureau of Standards plant at Boulder or possibly the earlier Herrick L. Johnston plants, but none of these was "standard."

On 6 June the persevering Rae tried again to obtain acceptance of his original proposal for a complete airplane development but failed once more. The meeting ended with three unresolved issues: airframe work, use of hydrogen in conventional engines, and burning hydrogen in an afterburner, as proposed in Rex II.[41] On 27 June, Rae's frustrations must have reached the breaking point for in a meeting with Wright

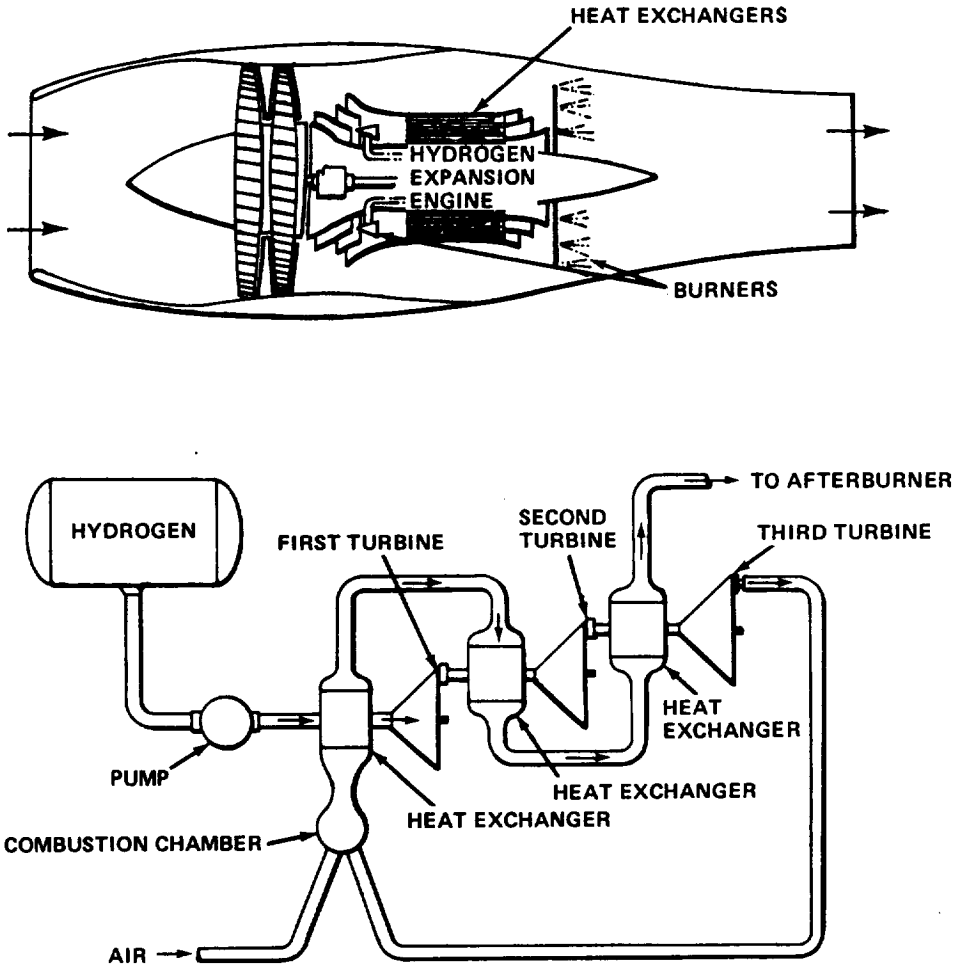


Fig. 32. Rex III engine system. Heat from burning hydrogen with air is transferred by means of heat exchangers to hydrogen on its way to the combustion chamber. The heated hydrogen drives turbines prior to combustion. There are three heat exchangers and three turbines. The turbines power a two-stage air fan or compressor. After leaving the last turbine, the hydrogen is injected and burned in the airstream in the afterburner and the expansion of the hot gas through the nozzle produces thrust. From R. S. Rae, "Various Engine Cycles Using Hydrogen as a Working Fluid and as a Fuel," Twelfth Annual Flight Propulsion Meeting, Institute of Aeronautical Sciences, Cleveland, 14 Mar. 1957.

Field officials, including a judge advocate, he refused to sign a contract with the Air Force, claiming that it neglected his patent rights.*

Meanwhile, individuals in other organizations were becoming interested in hydrogen. Silverstein of NACA had completed his analysis in April 1955 and

*On the same day, Rae's attorney filed a patent application for a multistage, high-altitude engine with a single combustion stage (518049). On 18 Oct. 1960, he was granted patent 2956402 for Rex III.

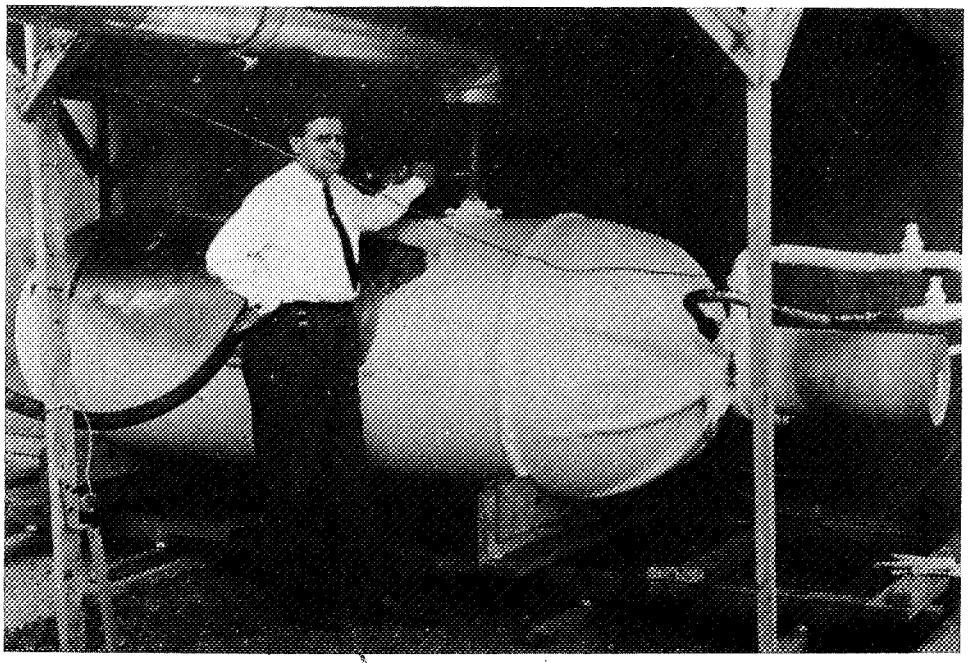


Fig. 33. Randolph Samuel Rae, creator of the Rex engines using liquid hydrogen as fuel, shown beside an experimental liquid hydrogen tank, ca. 1955. (Courtesy of R. S. Rae.)

according to one Air Force observer, "took to the road" making a circuit of high-level Air Force officials. One of these was Lt. Gen. Thomas Power, commander of the ARDC.[42] On 7 July, Power and Gen. Marvin Demler were briefed by WADC on the Rex program, with results that became evident from Appold's actions the following day. In discussions with his staff, Appold expressed concern about the Rex program, asked questions about the approach, the scope, and whether to go forward or cancel. He asked for a recommendation based on a comparison between the Rex and conventional engines available in the same time.[43] On 16 July, ARDC authorized WADC to study high-altitude engines with a two-pronged approach. One was to use conventional engines and the other, a new propulsion system for altitudes to 30 500 meters.[44] This essentially reiterated the ARDC directive of the previous year, but the sense of urgency had increased.

During July and August 1955, negotiations with Rae and Garrett continued without much success. On 25 August, Rae again refused to sign a contract, citing the inclusion of a study task as his reason. According to the notes of Frank Patella of the power plant laboratory who attended the meeting, Rae's position was: "The Garrett Corporation wants a development contract at this time and will not go along with anything less." Finally, however, after much additional negotiation and revision of work statements, two contracts with Garrett were signed in October 1955. One, coming from PR 303, was not far from what the power plant laboratory had originally specified. The other, from PR 339, was to study liquid hydrogen tanks. The two totaled $3 284 000—over four times the combined amount of the United Aircraft and Beech Aircraft contracts that had been in effect since June.[45]

When the Rex division of Garrett received its two contracts from the Air Force, after five months of hard negotiating, there was a big party and celebration. The staff was confident that they were at last firmly on the road to engine development and a great future.[46] Yet this was not to be, for the contract contained provisions that were to eventually knock Garrett out of the major competition.

Shift from Subsonic to Supersonic Aircraft

When Rae received the final work statement of the engine contract, he was disappointed to find that it specified only a supersonic airplane and a shorter range than he had been urging.[47] Rae's interest was in very long-range, high-altitude aircraft, with speed a secondary consideration. His early proposals for essentially a low-powered glider reflected this interest. His early engines used very small diameter turbines—on the order of 20 centimeters—and this was one reason he and Garrett had been attracted to each other, for small turbines were one of Garrett's specialties. During the long contract negotiations in the spring and summer of 1955, Rae still favored subsonic speeds, but the Air Force was more interested in a supersonic airplane at high altitude and would sacrifice range to get it. This was consistent with the Air Force desire for a superior airplane to supplant the subsonic U-2—superior both in altitude and in speed.

In the negotiations, Rae had gained funds for an airplane design study using the Rex engine. After receiving the work statement specifying a supersonic airplane, the Rex division prepared a "Problem Statement for Aircraft Studies" dated 7 November 1955 and negotiated a contract with Kelly Johnson at the Skunk Works. The problem statement specified Rex engines in pods for wing mounting. The size and weight of the pods with engines were given, as well as engine thrust and specific fuel consumption.[48] The pod diameter, essentially that of the engine inlet, was 122 centimeters, which meant an engine much larger than Rae's original concept; but the engineers of Garrett's Rex division did not feel that the larger sizes would be a major problem to develop.

During the course of the study, the engineers at the Skunk Works found that the thrust specified by Garrett was too low for their design needs. Agreements were reached with the Rex division on extrapolation of the engine data for engines of larger thrust and data giving specific fuel consumption as a function of Mach number. With these, the designers at the Skunk Works chose a cruise speed of Mach 2.25 and an engine with a thrust 50 percent higher than Garrett had originally specified. The larger thrust meant an engine with an inlet diameter of 150 centimeters. The engine now was considerably larger than machinery within Garrett's experience, but this did not deter the company. Some individuals within the Air Force, however, began to doubt whether Garrett was the best contractor for the engine.

The Lockheed study of a hydrogen-fueled airplane was completed and reported by the end of January 1956. Two configurations, both powered by Rex III engines of the larger thrust, were selected. The preferred design, designated CL-325-1, had a straight, thin wing and a slender fuselage. It was made of aluminum alloy with a single liquid hydrogen fuel tank in the fuselage. The second configuration, CL-325-2, used droppable auxiliary wing tanks, which reduced the airplane size and weight by about 15 percent. The CL-325 wing was lightly loaded, i.e., the wing had to support a

comparatively low weight per unit area. Its thrust per unit weight was also low, which required a long runway for takeoff. The characteristics of the CL-325, taken from the Lockheed report, are given by table 4.[49]

The Garrett engine contract, which began 15 October 1955, called for engine analysis and selection of the optimum one. The Rex division of Garrett, however, had been at work for some time before the contract and had already selected Rex III and had specified it for the Lockheed study beginning in November.[50]

The first Garrett engine report, covering the first four months of the contract, was "Rex Engine Cycle and Selection," 15 February 1956, with the Lockheed report included as an appendix. The report concluded that the Rex III was the optimum engine and that Air Force mission requirements could be met. It also concluded that a Rex III with a thrust of 17800 newtons at 30500 meters altitude and Mach 2.25 was feasible; its specific fuel consumption would be less than 1360 kilograms per hour and dry mass less than 1995 kilograms. Other design data were given. The engine described had a thrust slightly greater than that selected by Johnson in the airplane design and reflected Garrett's confidence that they could develop the larger engine.

Garrett sent a team to Wright Field on 15 February to give an oral summary of the report. The members of the team were in high spirits, looking forward to a favorable reaction. They had been told that if the audience did not ask a lot of questions, it meant

TABLE 4.—*Characteristics of CL-325-1 Hydrogen-Fueled Airplane*

Dimensions	
Length, m	46.73
Wing span, m	24.35
Height, m	8.71
Wing area, sq. m	209
Wing aspect ratio	2.5
Mass, kg	
Take-off	20731
Landing	14486
Empty	13352
Payload	680
Liquid hydrogen	6553
Engines	
Number	2
Type	Rex III
Thrust, each engine, take-off and climb, N	20016
Rated thrust, each engine, at 30500 m, N	16680
Performance	
Take-off distance, m	1402
Rate of climb at sea-level, m/s	8.9
Equivalent air speed during climb, m/s	79
Cruise Mach number	2.25
Radius (to target), km	2797
Climb and descent distance, km	556
Landing distance, m	640
Stall speed at landing, m/s	37

From Lockheed Aircraft Corp. report 11195, attached to report by J. L. Bartlett, Jr., I. M. Goldsmith, and A. Shaffer, "Rex Engine Cycle Study and Selection," report RD-14-R, Rex Div., Garrett Corp., 15 Feb. 1956.

trouble. Not many questions were asked; and that night, in the hotel room, the members of the team sat around trying to figure out what had gone wrong.[51]

What had gone wrong was that members of the audience, particularly those in the power plant laboratory, were beginning to realize that Garrett was talking about a whole new ball game. Gone was the simple, ingenious, new engine with its small turbines. In its place was a large, complex engine, with compressors and turbines about the size of those in contemporary turbojet engines. In addition, there were heat exchangers using hot combustion gases, something no one had yet attempted to develop. Rex III was considerably more complex than a turbojet engine and had other problems. Frank Patella, the laboratory's contract manager for the Rex engine study, noted in his log that Garrett apparently did not realize the problems involved in the proposed three-speed gearbox or the heat exchangers.[52] The Wright Field experts may also have been troubled by Rae's assurance that liquid hydrogen production facilities would cover the development needs for the larger engine.

Garrett Loses the Fight

The 15 February 1956 presentation was the turning point. Garrett's relationship with the Air Force would be downhill from that time on. Both sides had begun the relationship with great expectations and in good faith; but step by step, the size and complexity of Garrett's proposed engines grew and ultimately destroyed the company's prospects. On the Air Force side, the need to involve a well-established engine manufacturer was seen as early as August 1954, but it took time for this position to become the dominant consideration.

Nine days after Garrett's presentation; members of the power plant laboratory staff reported to Col. Harold Robbins of ARDC headquarters. Robbins, in turn, was to brief Gen. Thomas S. Power, ARDC's commander, on 27 February. Frank Patella was among those who talked with Robbins and he noted in his diary the main points of the briefing: Garrett did not have the facilities for component tests, the tools to manufacture, or the experience needed for the large engine, Rex III. There was considerable doubt among the Air Force propulsion experts that Garrett could develop such capability in time to meet the urgent need, for all agreed that the development of a special engine for high altitude operation merited a crash program. Robbins presumably conveyed these conclusions to Power in his briefing three days later.

Back at Wright Field, power plant experts continued their analysis of the Rex engine and Garrett's capabilities to develop it. On 1 March 1956, General Haugen, commander of WADC, was briefed on the Rex situation by B. A. Wolfe of the power plant laboratory. The Rex I engine, 60 centimeters in diameter, had been considered within Garrett's capabilities; but the 150-centimeter Rex III was clearly beyond Garrett's development and production facilities. The consensus was that to proceed with the Rex III development by Garrett would be sheer folly. On 5 March 1956 another conference took place, this time between working level personnel from the development and material groups. The participants again concluded that Garrett did not then have the capability to develop the engine and that it might take 8–10 years to

develop it unless a crash program were started. The power plant laboratory representatives pointed out that other engine manufacturers were now proposing essentially the same type of engine as Rex III.[53] The problem was being studied at all Air Force levels, from headquarters on down.

In the midst of these conferences, Garrett received a serious blow. The company had been urging the government to provide a liquid hydrogen plant on the government-owned land within their Phoenix facility. The city of Phoenix learned of this proposal and acted to prohibit Garrett from working with hydrogen within the city limits. This development set off a new round of conferences and staff studies within the government. On 22 March 1956, Lt. Gen. Power, commander of ARDC, recommended to the Air Materiel Command that a favorable atmosphere be sought whereby a major engine manufacturer could acquire Garrett's and Rae's interests in the Rex engine. If this could be done, the Garrett contract could be terminated and proposals solicited from major engine manufacturers.[54] Power's proposal was backed by a detailed staff study.[55] Philip Richie, at the working level in AMC, objected to the conclusions of the staff study and wrote a point-by-point rebuttal. Richie recommended that a committee be appointed to make a detailed study of the problem and use it either to convince Garrett that it was in the country's best interest to go elsewhere or use it to explain to others why the Air Force stayed with Garrett. On 10 May, Richie's recommendation was backed by his boss, Col. Merle R. Williams, WADC procurement chief, so the Air Force remained locked in an internal struggle over what to do about Garrett.[56]

Meanwhile, Bertram N. Snow, vice president of the Garrett Corporation, wrote to WADC on 12 May 1956, pointing out several problems. A remote facility was required to test with hydrogen; since none was presently available, there would be a considerable delay in carrying out the existing contract. He proposed to amend the contract to allow engine development of a prototype meeting the 50-hour test specification and to authorize the necessary facilities. If a hydrogen generating plant could not be provided by the government, Snow proposed to try for a commercial product on contract. He estimated that the prototype engine could be developed in four years, with a program and facility cost of $72.5 million. Garrett followed up this proposal with a presentation two days later: the Garrett board of directors had decided that while the company could not handle large-scale production of the engine, it could handle limited production. Two engine manufacturers had made overtures to Garrett but had been rebuffed.[57]

Sometime in the spring, the perceptive Snow sensed the changed Air Force attitudes towards Garrett. He and Rae visited General Power in Baltimore to protest. Power listened to them and promised that they would receive a reply, but that it would come from General Rawlings of the Air Materiel Command. The meeting with Rawlings was held on 18 May 1956, and Snow was told bluntly that timely and successful development of the proposed engine could be done only by a major engine manufacturer. On 18 June, Snow wrote a strong letter of protest to Assistant Secretary of the Air Force for Materiel, Dudley C. Sharpe, stating Garrett's position and included a chronology of events. He made five points: (1) Garrett owned patent rights, (2) the Air Force had encouraged Garrett to develop the Rex engine, (3) Air Force

working level organizations had ignored Garrett's proprietary rights.* (4) Garrett's performance had been satisfactory, and (5) Garrett was willing to negotiate in the public interest. The thrust of Snow's letter was two proposals that eliminated the need for the government to furnish facilities. The first proposed that Garrett be given the prime contract for engine development, and Garrett would subcontract to a larger engine manufacturer any work it could not handle. The second proposed that Garrett be given the engine production contract and if production needs exceeded what Garrett could provide with its own resources, then Garrett would license a larger engine manufacturer to make the additional units.[58]

This appeal to Sharpe and visits to high-level government officials by Garrett officials did little to resolve the basic issues. Although Garrett continued working on its original contract, with several extensions, that work was essentially out of the mainstream of Air Force R&D projects. Phase I of the Garrett contract, engine analyses and selection, had been completed and presented on 15 February 1956.[59] Phase II, a thorough and comprehensive preliminary design study of the Rex III engine, was completed in May 1956.[60] Phase III, to design, fabricate, and test combustors, turbines, fuel pumps, gear boxes, and heat exchangers, continued until 1 February 1957, when the objectives were revised to be general research and development rather than specific to the Rex III engine design. On 18 October 1957, Garrett received a directive to stop all work on the contract except for the preparation of a final report. This report, in several volumes, was completed in 1958.[61]

What Went Wrong

What went wrong in the Rae–Garrett–Air Force relationship? Lt. Col. Langdon F. Ayers, who was in the midst of the Rex events from beginning to end, summarized his view in August 1956. He saw Rex as the "classical example" of the problem of exploiting innovations. He believed that established, old-time engine companies were not likely to recognize or develop innovations because of vested interests. When an individual proposed a promising engine innovation, Ayers thought that the government should move the innovation, as fast as possible, to an established engine company and reward the inventor.[62]

With the perspective of time, it is easy to see the errors made on both sides, but what can we learn from them? How can promising innovations be nurtured until they develop into a benefit for both originator and sponsor? There are no easy answers, but a few observations can be made.

An idea or concept in itself is of little or no value until it is transformed into something people need or want. In our free enterprise system, an innovator must develop his idea or else seek a suitable sponsor who then takes the risk of development. The development of an innovation as complex as an aircraft engine or an airplane requires considerable capital for facilities, equipment, and operating funds. If a sponsor already has these and is willing to use them to develop an innovation, the

*This was apparently with reference to an analysis by R. P. Carmichael, which will be discussed later. Garrett was also disturbed over the government's attitudes towards its patent rights.

innovator has made a fortunate alliance. Rae's case is tragic in that he twice chose sponsors who did not have the capability to meet his goals. Summers Gyroscope was clearly not suitable for more than studies and small component work. Garrett was suitable for developing small machinery and was willing to invest some of its own capital to expand, but it looked to a sponsor of its own, the government, to provide additional facilities and a development contract. The government was interested in Rae's idea but was not willing to sponsor the development of a company to exploit it, especially when there were suitable companies available. The government's position was sound, but perhaps errors of judgment were made in encouraging Garrett and later, when a contrary view became prevalent, of not promptly informing the company. Perhaps Rae, as inventor, and Garrett, as a company ready to develop the invention, erred in seeking to make too big a step in the beginning. They seemed unaware of the danger of proposing larger and larger engines until they found themselves out of the ball park. The urgency felt by the Air Force to develop an airplane superior to the U-2 settled the matter.

How can the government benefit from the ideas of lone inventors? This has been the subject of much study and a single case history can scarcely provide the answer. The Rex history does show, however, that the choice of a sponsor to exploit an innovation is all-important and that a goal may sometimes be reached better by a series of small steps rather than a gamble on one giant leap.

Other Interests in Hydrogen

During the last quarter of 1955 and concurrent with Garrett's Air Force contract, two other events occurred to broaden interest in hydrogen for aircraft.

In October, the Fuels and Propulsion Panel of the USAF Scientific Advisory Board met and considered superfuels and reconnaissance vehicles.* On superfuels, the panel noted that hydrogen was one of three main lines of attack. It was most anxious to see engine studies and preliminary aircraft design studies directed towards application of hydrogen for aircraft propulsion. Further studies by the NACA since the March meeting continued to show excellent combustion characteristics of hydrogen. The panel believed that power plant development using hydrogen would encounter minimum difficulties, but an aircraft to use low-density fuel would require substantial redesign. Also noted was a need to study the possible adaptation of hydrogen to current aircraft or missiles.[63]

Anticipating the panel's conclusions, the Air Force included $4.5 million in the FY 1957 budget request for development related to hydrogen, a substantial increase over the $1 million of the previous year.

In November, Wright Field issued a technical note, "Cycle Performance of Some Selected Engine Configurations Using Liquid Hydrogen Fuel," in which Robert P. Carmichael analyzed nine engine systems using hydrogen as a coolant and a turbine working fluid as well as a fuel.[64]

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*The meeting, held on 21 October 1955, was attended by Mark M. Mills, chairman, W. D. Rannie, Addison M. Rothrock, E. S. Taylor, and Gale Young. SAB files, Pentagon.

He also compared the performance of these engines with a conventional turbojet. Among his conclusions: some of the hydrogen engines gave superior performance compared to conventional turbojets; precooling the incoming air with liquid hydrogen increased the mass flow through the engine; both precooling and use of hydrogen turbines increased combustion pressure and permitted operation at higher altitudes with smaller combustors than conventional jets using hydrocarbon fuels.

Carmichael's analysis was distributed to nine major aircraft engine manufacturers and seven airframe manufacturers, causing Garrett to complain that their proprietary rights had been violated (pp. 136–37).* In spite of the complexity of some of the hydrogen engines, the note must have stirred up considerable interest in hydrogen within the aeronautical community.

Summary

The Air Force began planning work to achieve very-high-altitude flight in late 1952 and this resulted in successfully modifying the Martin RB-57, a later version of which is flying today. In 1954 Kelly Johnson of Lockheed, famed airplane designer, proposed a high-altitude reconnaissance airplane that was sponsored by the government. This became the U-2, which is also still flying.

In 1954, Randy Rae proposed a novel hydrogen-fueled subsonic airplane capable of high-altitude flight. Although never built, it spawned considerable interest and activity on the potential of hydrogen as a fuel. The Garrett Corporation acquired Rae's interests and pressed the Air Force for a contract to develop the airplane and its engine, but received only a study contract and some component work. As interest grew and specifications changed from a subsonic to supersonic airplane, the required engine power increased, which meant a much larger hydrogen-fueled engine than Rae originally envisioned. The growth in engine size effectively took Garrett, a maker of small turbines and aircraft components, out of the competition. The government considered it inappropriate to set up Garrett as a manufacturer of large aircraft engines when several capable and well-established companies were willing to do the same thing. Rae and Garrett placed reliance on their patents, and their relationships with the government made a case study of the frustrations of an innovator with a single customer and needing large resources. Some benefits resulted, however; by the end of 1955, interest in using hydrogen in aircraft had grown considerably.

*The allegation is questionable in view of Wright Field's long background in turborockets and research on hydrogen. The official response to Garrett indicated that no proprietary data had been used in the Carmichael report and that engine cycles in general are not proprietary.